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TM No. 841134

NAVAL UNDERWATER SYSTEMS CENTER
NEW LONDON LABORATORY
NEW LONDON, CONNECTICUT 06320

Technical Memorandum

DETECTION, CLASSIFICATION, AND EXTRACTION OF HELICOPTER-RADIATED NOISE

Date: 25 July 1984

Prepared by: Roger F. Dwyer
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ABSTRACT

Surface ships operating in conjunction with supporting helicopters may experience sonar performance degradation due to the accompanying interference from helicopter-radiated noise. The interference manifests itself in the time domain as impulses due to blade vortex interactions and in the frequency domain as harmonic components from both the main and tail rotors. But these components are not pure sinusoids. In addition, they have non-Gaussian probability distributions. They appear to be caused by frequency modulation due to the rotating blades.

The paper discusses detection and classification of helicopter-radiated noise from cumulative distribution function estimates, autocorrelation estimate, spectrum estimates, and from higher-order moment estimates. After the detection and classification problem is discussed a method to extract the interference by implementing a non-linearity in the frequency domain is presented. It is shown with real helicopter-radiated noise data that autocorrelation estimates can be improved by extracting the interfering components. The extracted components are also available as an enhanced time domain representation.

ADMINISTRATIVE INFORMATION

This technical memorandum was prepared under NUSC Project No. A75031/2, Data Adaptive Detection and Estimation, Principal Investigator Dr. R. F. Dwyer, (Code 3314). The Sponsoring Activity is The Office of the Naval Research, Program Element: 61153N, Research Project: RR014-05-01, Program Manger Dr. E. Wegman, ONR (411).

The author of this document is located at the Naval Underwater Systems Center, New London Laboratory, New London, Connecticut 06320.

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INTRODUCTION

This paper discusses aspects of detection, classification, and extraction of helicopter-radiated noise from acoustic measurements in the time and frequency domains. The measurements include cumulative distribution function (cdf) estimates and autocorrelation function estimates in the time domain; spectrum and higher-order estimates in the frequency domain. Although skew and other moment estimates may prove valuable for detection and classification, only kurtosis, estimated in the frequency domain and called frequency domain kurtosis (FDK), will be considered here. The FDK is defined as the ratio of the fourth-order central moment to the square of the second-order central moment for the same data set[1]. It represents a measure of the underlying probability distribution of the signal. Therefore, the FDK can be used as a measure to distinguish between stationary stable sinusoids and Gaussian signals from helicopter-radiated noise components which are non-Gaussian. The non-Gaussian nature of the components are due to the medium effects and the unsteady radiated noise components generated from the rotating blades. In the data set examined not all the components turned out to be non-Gaussian. However, many were. This additional information from the FDK estimate represents a measure in terms of a probability distribution that may prove useful for computer aided detection and classification purposes.

After detection and classification properties are discussed with real data the paper explores the possibility of extracting helicopter-radiated noise components by implementing a nonlinearity in the frequency domain so that sonar performance can be improved. As will be seen from the real data, helicopter-radiated noise has a highly complex structure. It consists of discrete frequency modulated components and broadband noise. The effects of the medium on the received data are also apparent.

In the time domain the radiated noise consists of impulses generated from blade vortex interactions[2,3,4]. The frequency domain results show what appear to be harmonically related components. These components rapidly change frequency with time due to the unsteady nature of the radiated noise from the rotating blades.

The first phase of the process consists of detection and classification of the radiated noise. Then the components are extracted by first transforming the data into the frequency domain by an FFT, passing the transformed data through an ideal nonlinearity and transforming back into the time domain[5].

The acoustical source used for this paper was an UH-1 helicopter. This was an advantage, because, the radiated noise from an UH-1 helicopter has been measured extensively and related to theoretical predictions[2,3,4]. Therefore our data results were compared with published findings. We found that both of our in-air and underwater acoustic measurements of an UH-1 helicopter essentially corroborate the published results. However, we have substantially extended the measurements previously reported in the literature.

In a real scenario all of the information available will be utilized for the detection and classification problem. We discuss measurements made in both the time and frequency domains. Therefore, the paper is organized

into three sections: time domain analyses, frequency domain analyses, and then the extraction procedure will be described.

TIME DOMAIN ANALYSES

The data for the time domain consist of time histories, cdf estimates and autocorrelation function estimates. Helicopter-radiated noise measured in air is shown in the top graph of figure 1. The periodically occurring impulses are due to blade vortex interactions which are sometimes called "blade slap." They occur approximately every 82 msec. This produces a fundamental frequency of 12 Hz from the main rotor. Similar underwater measurements reveal that the intervals between impulses are filled with ambient noise. Although impulses are occasionally seen depending on the radiated noise level, for the most part, underwater time histories are asked by ambient noise. To more precisely determine if impulses are present in the underwater data cdf estimates were made.

Since impulsive noise has a non-Gaussian probability distribution, the cdf estimate can be used as a clue to determine whether or not impulsive noise is present. This is done by comparing the cdf estimate of the data with a Gaussian cdf. In figure 2, three cdf estimates are plotted on Gaussian probability paper. The solid curve represents in air data, the circles are the underwater measurements and the broken curve represents a Gaussian distribution, and therefore, follows a straight line. Both in air and underwater measurements of helicopter-radiated noise deviate from a Gaussian distribution. The in-air data deviates from a Gaussian distribution in the high probability and low probability regions. Whereas, the underwater data only deviates from a Gaussian distribution in the low probability region or in the "tails" of the distribution. Therefore, in underwater applications, in order to use the non-Guassian distribution properly, as a classification clue for helicopter-radiated noise, a sufficiently large sample of data is required in order to estimate the tail region of the distribution.

From the time history of figure 1 it is apparent that the impulsive signature is a periodic function of time. Therefore, the autocorrelation function estimate can also be used as a detection and classification aid. Figure 3 compares the autocorrelation function estimates for in-air and underwater measurements. The top graph represents the in-air data. Again the periodic nature of the radiated noise is evident from the figure. The high autocorrelation values which do not decrease with increasing time delay correspond to the repetition of the impulses. The separation of the major peaks of 82 msec agree with the separation of the impulses of figure 1 and correspond with a main rotor fundamental frequency of approximately 12 Hz.

On the other hand, the underwater autocorrelation function estimate in the bottom graph of figure 3 shows that the separation of the major peaks are near 89 msec and which correspond with a main rotor fundamental frequency of approximately 11 Hz. However, the autocorrelation levels are less than the in-air levels and they decrease with increasing time delay. Apparently, due to the ambient noise in the underwater measurements.

The next section will discuss the frequency domain aspects of the radiated noise.

FREQUENCY DOMAIN ANALYSES

It appears that more additional information can be obtained in the frequency domain. A comparison of the estimated power spectrum for the in-air and underwater measurements of the helicopter-radiated noise sectrum appears in figure 4. The top graph represents the underwater data and the bottom graph the in-air results. These signatures are similar to each other and also agree with the published results [2].

For the under water data the 11 Hz fundamental from the main rotor is the first peak in the top graph. The corresponding harmonics from the main rotor are seen as multiples of the fundamental. The tail rotor's fundamental frequency is at 55 Hz and its corresponding harmonics are at 55 Hz multiples. An interesting result is that the sepctrum level for some of tail rotor's harmonics appear to be higher.

On the other hand, the 12 Hz fundamental for the main rotor in the in-air data is not obvious in the figure because the data was prefiltered with a high-pass filter. But the associated harmonics of 12 Hz are clearly seen. The tail rotor fundamental of about 62 hz and its associated harmonics are also clearly seen in the figure.

By observing the spectrogram of the radiated noise measured underwater, as shown in figure 5, it is revealed that the harmonic components are not pure sinusoids. Rather, each harmonic appears to be a frequency modulated function of time. This is caused by the differential doppler components generated by the opposite motion of each blade measured with respect to an observer on the ground as the helicopter approaches. In additon to this phenomenon, the frequency components appear to fade, from possibly multipath effects, over the duration of the spectrogram. The arrows in figure 5 corresponds to the main rotor and tail rotor harmonics.

Since both the frequency modulation and fading are caused by physical phenomena not under our control, additional statistical measurements may prove useful as a computer aid for detection and classification. In this regard, the higher-order estimate, kurtosis, is currently being studied.

For the underwater data, figure 6 compares the power spectrum estimate with its corresponding frequency domain kurtosis (FDK) estimate. As seen in the bottom figure many of the frequencies show high kurtosis levels indicating non-Gaussian processes. The first large peak is at 33 Hz which corresponds with one of the harmonics seen in the corresponding power spectrum. However, not all harmonics show high FDK levels. In addition several frequencies have high kurtosis but the corresponding power spectrum do not indicate signal peaks. The reason for this is that kurtosis is sensitive to the underlying probability distribution of the data whereas the power spectrum is sensitive to data's energy content.

The conclusions reached by the statistical analyses of the in-air and underwater helicopter-radiated noise measurements are as follows:

1. Helicopter (UH-1) radiated noise can be detected in the frequency domain by its narrowband components up to 400 Hz.

2. High-order spectral moments (kurtosis spectrum) indicate unsteady radiated frequency components.

3. Broadband radiated noise levels are measureable in the time and frequency domain.

4. The estimated cumulative distribution function in the time domain exhibit non-Gaussian characteristics.

In the next section preliminary results are discuss for the extraction of helicopter-radiated noise.

EXTRACTION OF NARROWBAND COMPONENTS

A method to extract narrowband components in the frequency domain was developed. It consists of first transforming the data into the frequency domain by an FFT, passing the transformed data through an ideal nonlinearity, and then transforming the data back into the time domain by an IFFT.

The preceeding sections discussed the characteristics of helicopter-radiated noise that are useful for detection and classification. Here we concentrate on the extraction of narrowband components to improve sonar performance. Once the narrowband components are identified they can be extracted by passing the data through a nonlinearity[5]. The output data with the narrowband components extracted may then be transformed back into the time domain for further processing. For example, the autocorrelation function of the desired signal may be estimated free of the interfering components. In addition, the extracted components are available as an enhanced time domain representation. This technique has been published in the open literature[5], therefore we will only present the results of extracting the helicopter radiated noise. However, this method can extract highly dynamic narrowband and harmonically related narrowband components. Also, fixed sinusoids or lines can also be extracted. But there are other methods to extract lines. Our method can be considered a generalization of pure line removing algorithms since a much wider class of data can be extracted which is not possibly for those other methods.

The autocorrelation function will be used to demonstrate the effectiveness of extracting some of the components of helicopter-radiated noise. An estimate of the autocorrelation function of the radiated noise is shown in the top graph of figure 7. The periodic peaks correspond to the recurrent impulses. This data was transformed into the frequency domain by an FFT, then the frequency components were passed through a nonlinearity and transformed back into the time domain by an IFFT. The resultant autocorrelation function estimate is shown in the bottom graph of figure 7. Now, the periodic peaks are not present, which indicates that we were able to extract the impulsive noise. This is also seen to be true to a large extent from the bottom graph of figure 1 which shows the resultant time history. In addition, the noise variance measured in the time domain was reduced by several decibels.

Our next example demonstrates the masking effect of helicopter-radiated noise on a sinusoidal signal. In the top graph of figure 8 the autocorrelation function estimate of a sinsoidal signal plus

helicopter-radiated noise is shown. The bottom graph is the resultant autocorrelation function estimate after the helicopter-radiated noise components have been extracted. The corresponding time histories are shown in figure 9.

These results are only preliminary but they do suggest the possibility of sonar performance improvements by extracting helicopter-radiated noise.

SUMMARY

Real helicopter-radiated noise data have been presented. Time domain analyses were considered as a means to detect and classify the radiated noise. This information included, raw data time histories, cdf's estimates, and autocorrelation function estimates. However, it appeared that more information was present in the frequency domain analyses. In this domain power spectrum and FDK estimates were obtained from the real data. Both the harmonic structure of the signature and the non-Gaussian nature of the radiated noise represent clues for classification and extraction. Examples demonstrated the effectiveness of extracting some of the radiated components by passing the data through a nonlinearity implemented in the frequency domain. These results are only preliminary but they do suggest the possibility of sonar performance improvements in environments in which helicopter-radiated noise interferes with reception of desired signals.

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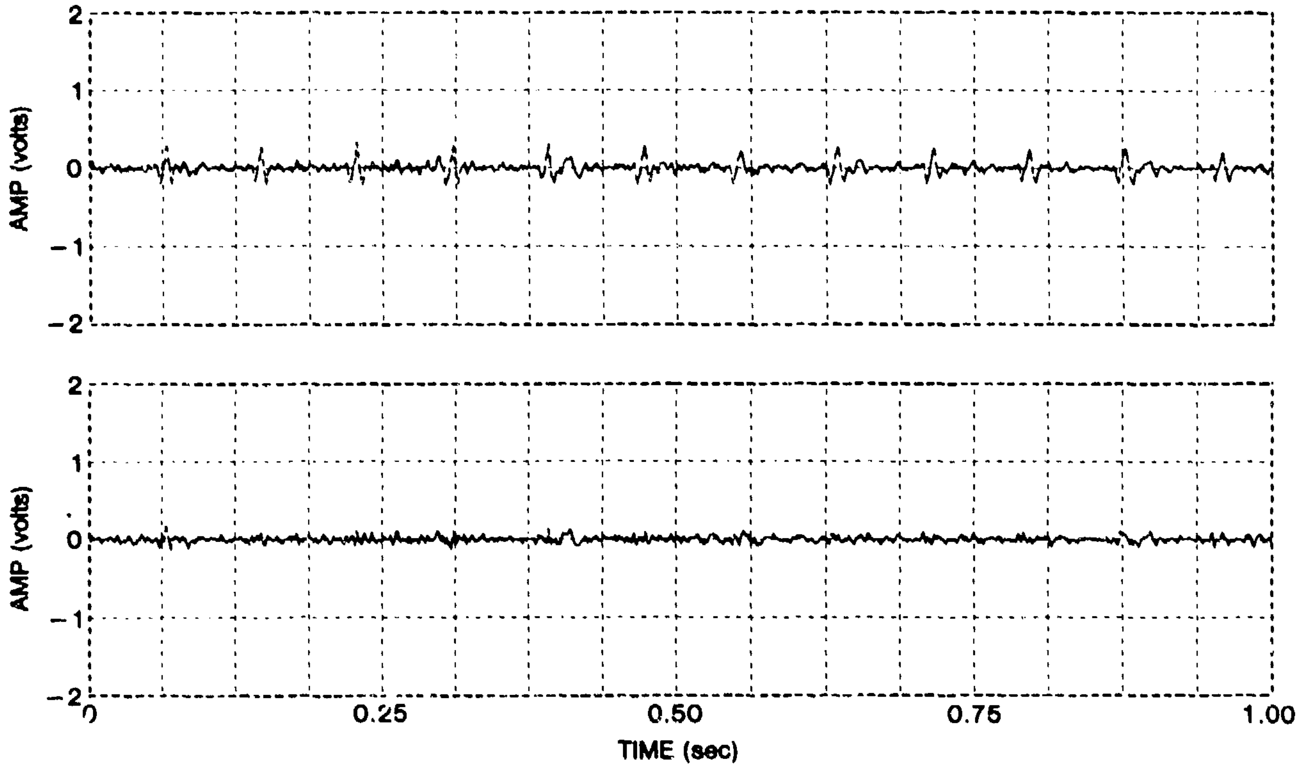

Figure 1. Helicopter-Radiated Noise Time Histories: (Top) In-Air Data, (Bottom) Impulses Extracted by Frequency Domain Processing.

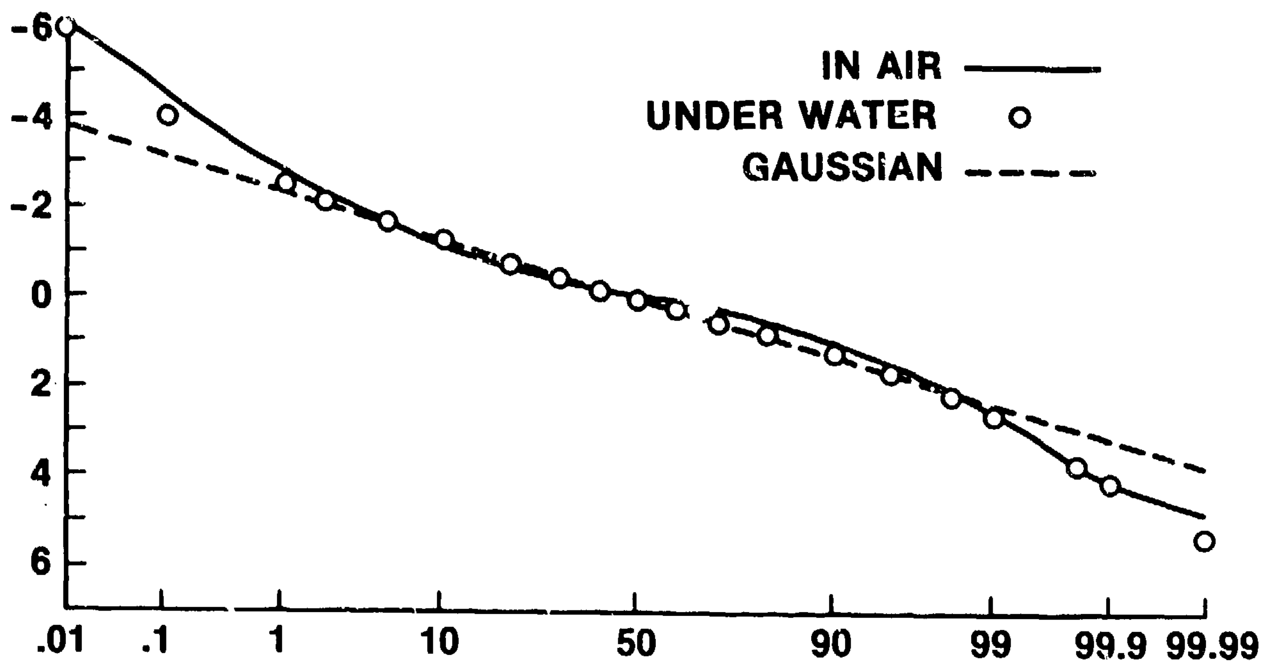

Figure 2. Comulative Distribution Function Estimate of In-Air and Underwater Measurements.

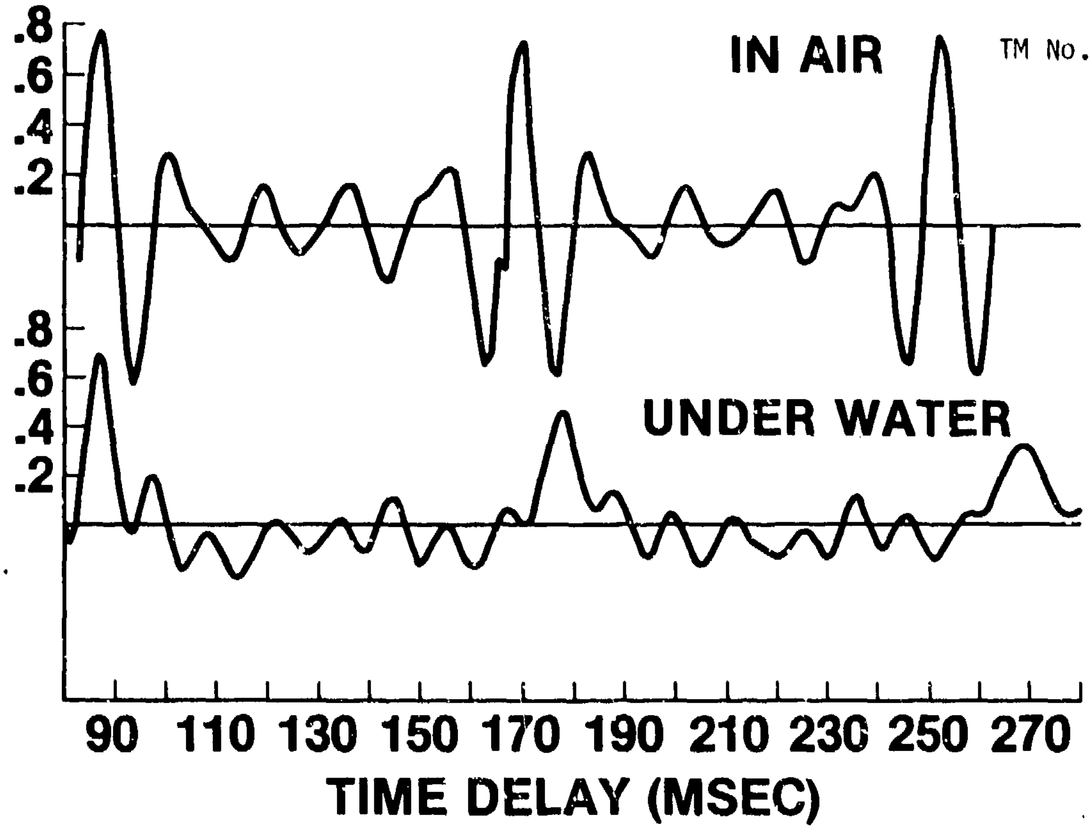

Figure 3. Autocorrelation Function Estimates for In-Air and Underwater Measurements.

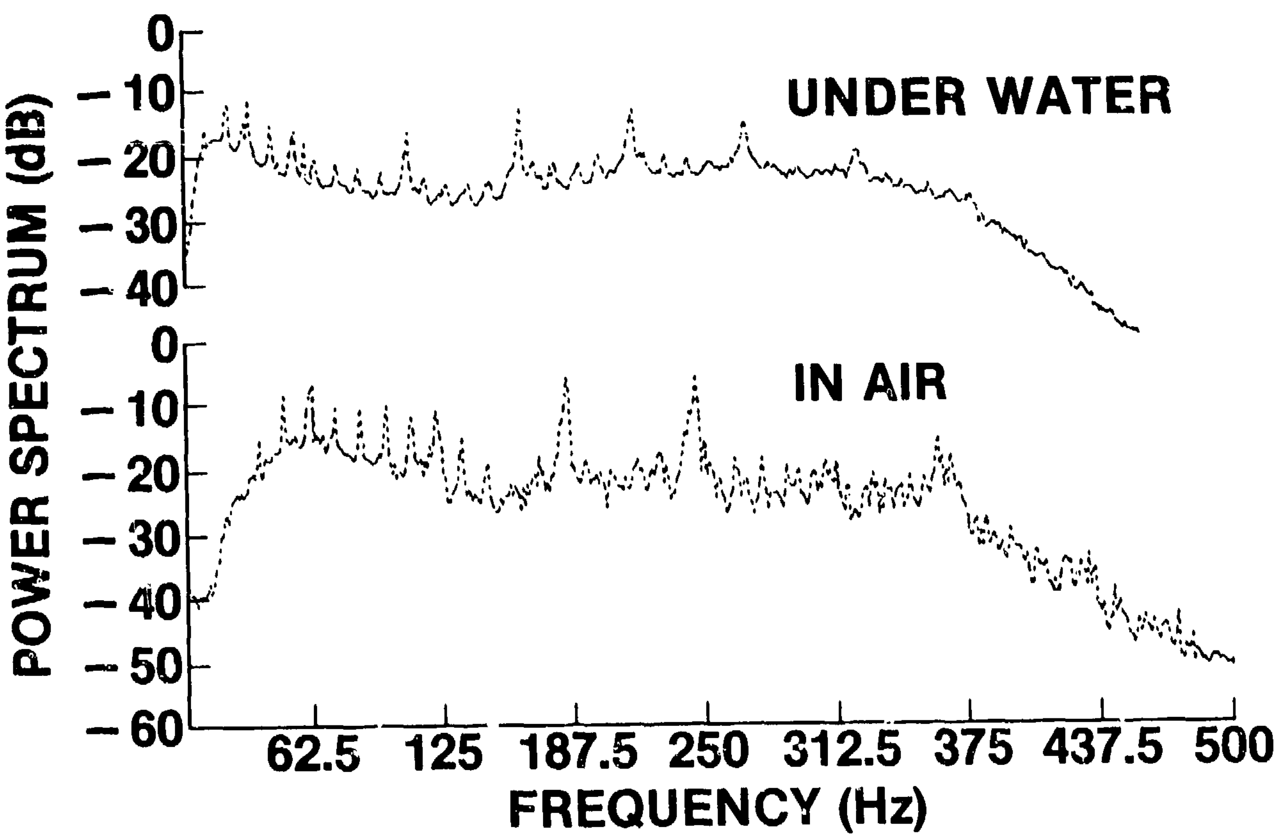

Figure 4. Power Spectrum Estimate of In-Air and Underwater Measurements.

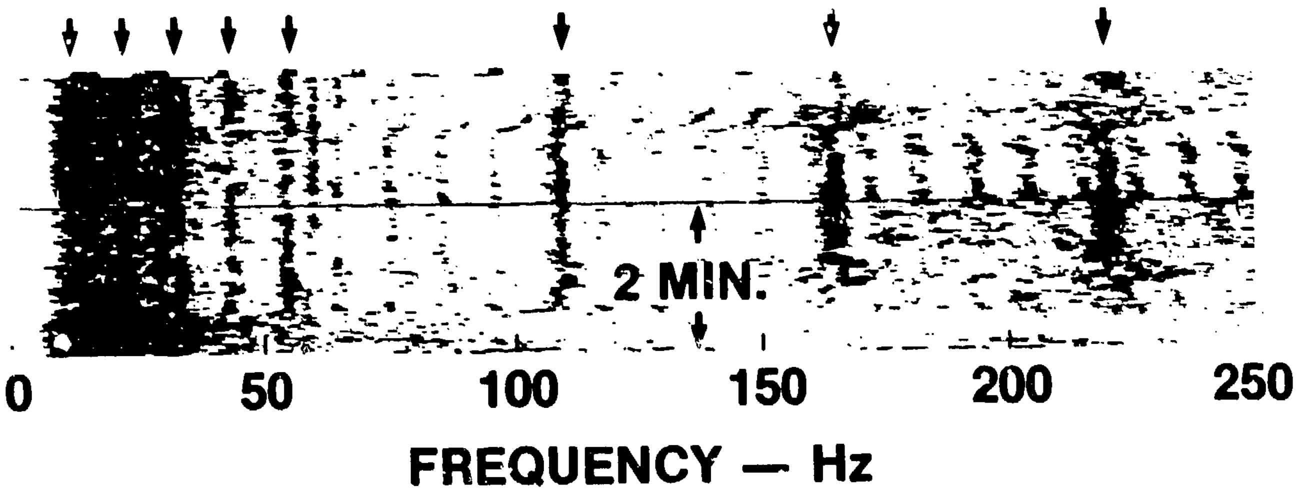

Figure 5. Spectrogram of Underwater Data.

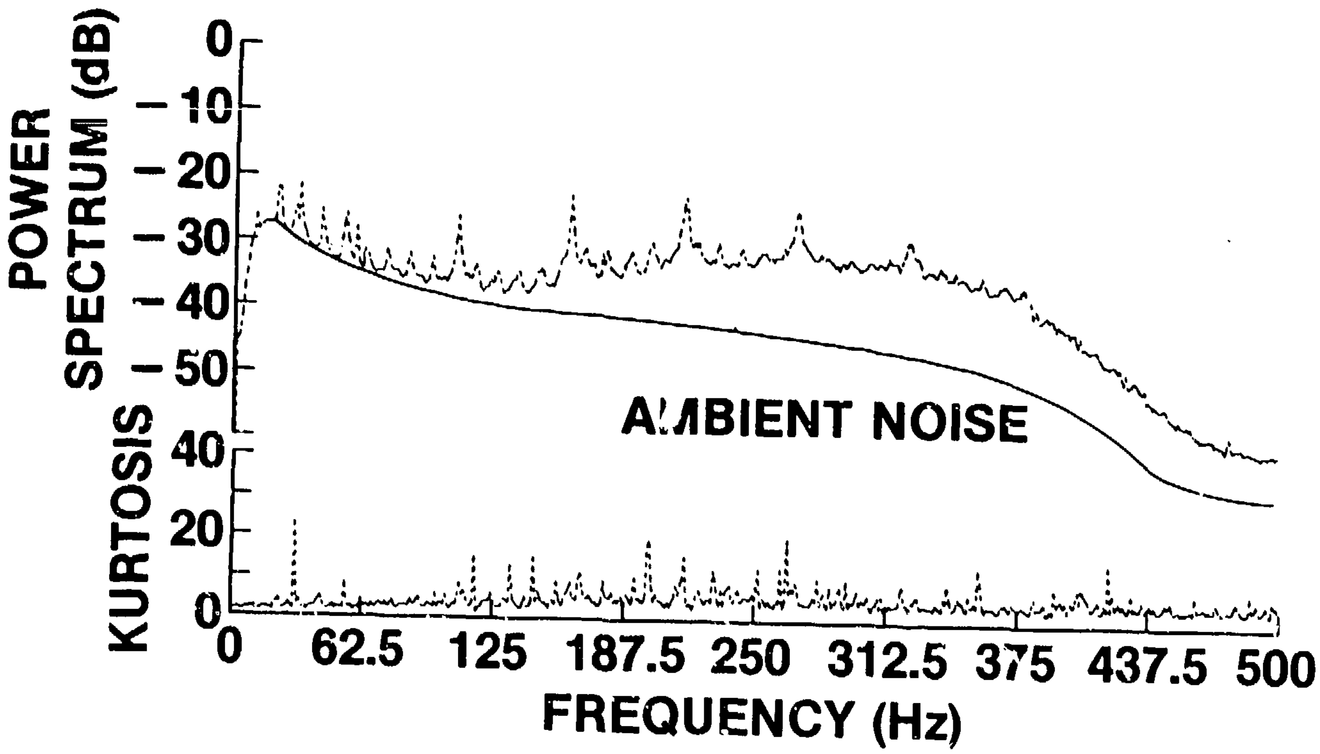

Figure 6. (Top) Power Spectrum Estimate, (Bottom) Frequency Domain Kurtosis Estimate.

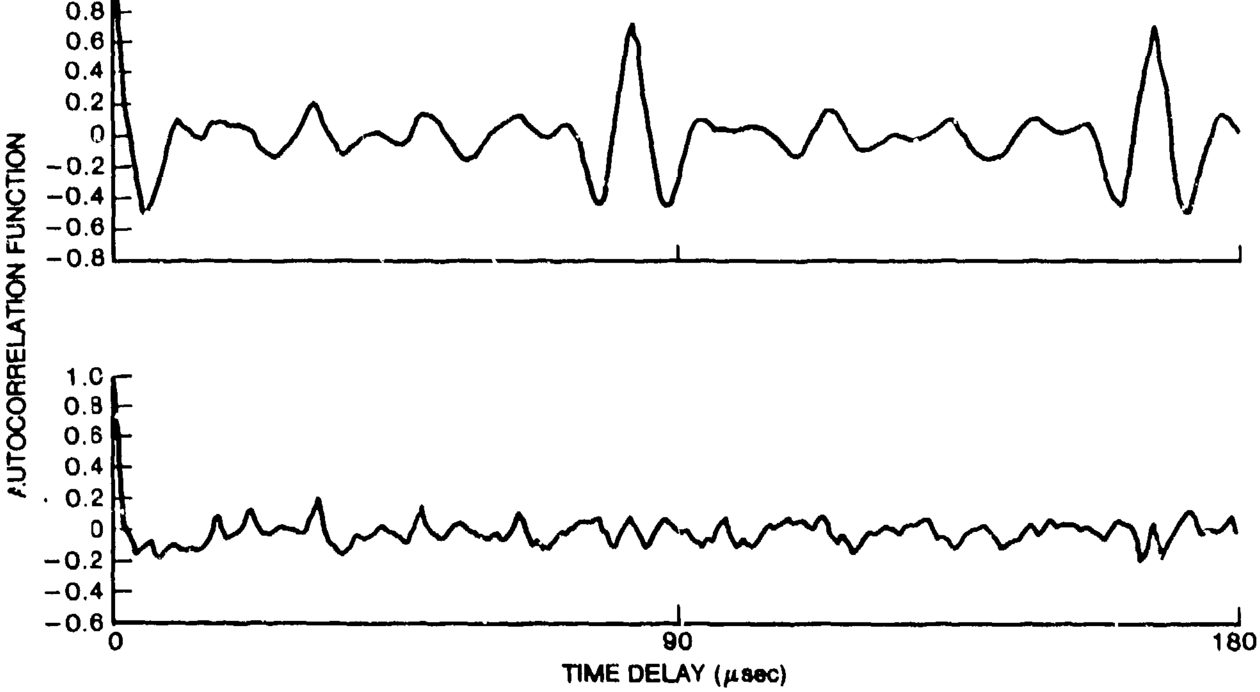

Figure 7. Autocorrelation Function Estimates. (Top) In-Air Data, (Bottom) Impulses Extracted by Frequency Domain Processing.

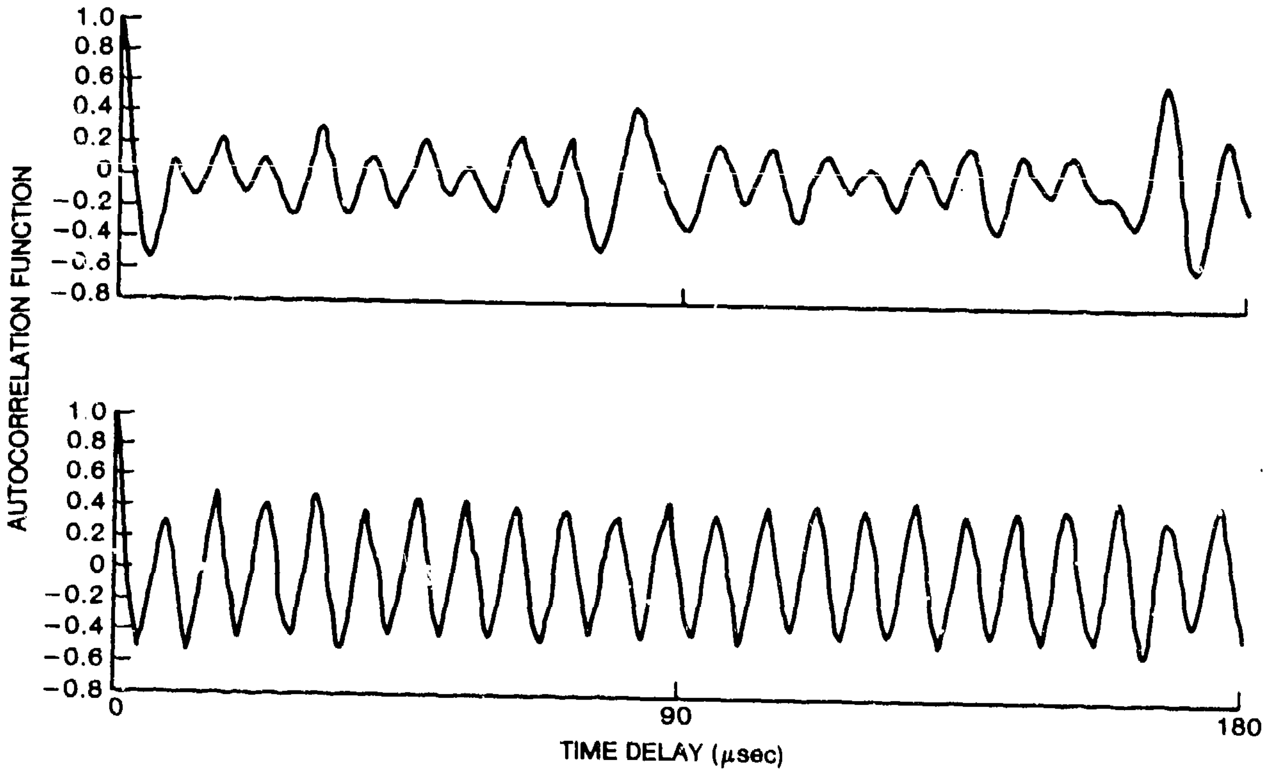

Figure 8. Autocorrelation Function Estimates - Top-In Air Data with Additive Sinusoid, Bottom-Helicopter-Radiated Noise Components Extracted

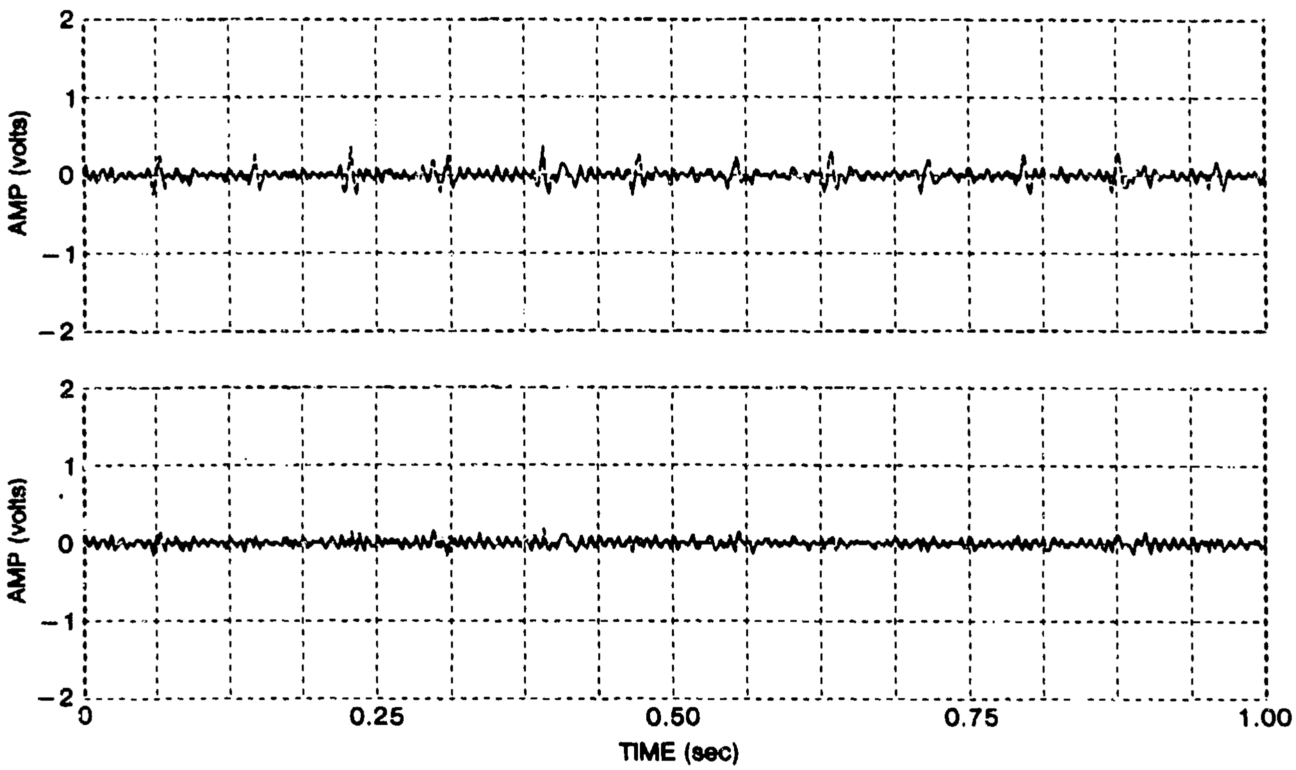

Figure 9. Time Histories: (Top) In-Air Data with Additive Sinusoid, (Bottom) Helicopter-Radiated Noise Extracted.

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DETECTION CLASSIFICATION ON EXTRACTION OF
HELICOPTER-RADIATED NOISE
Roger F. Dwyer
Surface Ship Sonar Department
25 July 1984
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